The Origin of Parsec-Scale Gaseous and Stellar Disks in the Galactic Center and AGNs

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Abstract. The Galactic center stellar disk and the circumnuclear ring provide a unique opportunity to study in detail the dynamics and physical conditions of distant molecular disks in the nuclei of galaxies. One of the key questions is how these disks form so close to their host black holes and under what condition they form stars in a tidally stressed environment. We argue that disk formation around a massive black hole is due to partial accretion of extended molecular clouds that temporarily pass through the central region of the Galaxy. The cancellation of angular momentum of the gravitationally focused gas naturally creates a compact gaseous disk. The disk can potentially become gravitationally unstable and form stars. We apply these ideas to explain the origin of sub-parsec megamaser disks found in the nuclei of Seyfert 2 galaxies. We show that an empirical scaling relation between the mass of the black hole and the size of the disk can be understood in the context of the cloud capture scenario. We conclude that the stellar and gas disks found in our Galactic center act as a bridge to further our understanding of more distant mega-maser disks in the nuclei of Seyfert 2 galaxies.

1. Introduction

Understanding the formation of massive young stars in the immediate vicinity of massive black holes is challenging. Two plausible models for the origin of the disk of massive stars orbiting Sgr A*, the 4×10^6 $M_\odot$ black hole at the Galactic center, have been proposed, namely, in-situ star formation and the dynamical migration of star clusters (see Genzel, Eisenhauer and Gillessen 2010; Levin and Beloborodov 2003; Gerhard 2001; Nayakshin et al. 2007). It has become clear that the in-situ star formation model can account for present observations better than the migration scenario in which a young star cluster undergoes dynamical friction and spirals toward the Galactic center. The question then arises as to what extent disk formation near Sgr A* can provide insight in the formation of sub-parsec gaseous disks orbiting supermassive black holes in AGNs. To address this question, we will first focus on the origin of Galactic center stellar and molecular disks near Sgr A* followed by AGN disks in the context of partial cloud capture by the massive black hole. We then discuss observational signatures such as the scaling relation between the mass of the black hole and the size of the disk as well as the recoil of the black hole in the context of the cloud capture scenario. A more detailed account of the results presented

here can be found in Wardle and Yusef-Zadeh (2008, Paper I), Yusef-Zadeh et al. (2009, Paper II) and Wardle and Yusef-Zadeh (2011, Paper III).

2. Galactic Center Young Stellar Disks

Observations of our Galactic center indicate that there are about 100 massive young stars distributed within one or two disks with a sharp inner edge (Paumard et al. 2006; Lu et al. 2010). In the in-situ formation scenario, an interstellar cloud is tidally disrupted and captured by Sgr A* (Nayakshin, Cuadra & Spingel 2007). There are two issues that are of interest in the context of this mode of star formation. One is related to the mechanism in which massive stars are formed in a disk. If the gas disk is significantly massive, it can become gravitationally unstable resulting in the fragmentation and formation of stars. A cooling self-gravitating gas disk around a black hole becomes unstable to fragmentation on a dynamical time scale if Toomre's Q$<$ 1. In this picture, the strong tidal force by the black hole plays a dual role. On the one hand, tidal shear acting against self-gravity stretches the cloud in the radial direction, making it more difficult for the cloud to fragment. On the other hand, the gas is tidally squeezed in the vertical direction, parallel to the disk axis, thus, making it easier to resists the gravitational stress by increasing the gas density to the Roche's critical value. As the cooling time is comparable to the dynamical time scale, stars in a hot disk are formed in self-gravitating clumps with a range of eccentricities and inclinations as the disk circularizes (Nayakshin et al. 2007; Wardle and Yusef-Zadeh 2008; Bonnel and Rice 2008; Alig et al. 2011). Simulations of the capture of a cloud suggests that star formation during such an event will occur before the disk is fully circularized and becomes dynamically cold (Mapelli et al. 2008). This is in contrast to a cold self-gravitating disk that forms stars with small eccentricities. Large eccentricities could not easily be built up from initial circular orbits in a cold disk, thus, the hot disk scenario may better explain the observed stellar kinematics

The second issue is related the mechanism in which a cloud loses angular momentum to form a disk so close to Sgr A*. The cloud has no means of getting rid of its angular momentum and it is difficult and rare to capture a compact cloud by a massive black hole without being engulfed. However, nature provides an easier mechanism to bring the gaseous material closer in to the black hole. This is done by the capture of material from an extended cloud passing on opposite sides of the black hole, thus allowing the loss of much of the angular momentum of gravitationally focused gas. The gaseous material with large impact parameters can settle much closer to the black hole, thus higher gas density is achieved. Given the level of asymmetry and inhomogeneity in the spatial distribution of the cloud, the cloud capture event may even account for multiple counter-rotating disks with different inclinations. Figure 1 shows a diagram of a cloud impacting Sgr A*. The gravitational focusing of an incoming molecular cloud is shown in the top panel whereas the outer region of the cloud that is not captured continuous its motion in the direction away from Sgr A*. The inner region of the cloud is carved out, captured and circularized to form a disk.

3. Galactic Center Molecular Disk

Multi-wavelength studies of the Galactic center show that a 2-parsec clumpy molecular ring circles Sgr A* with a rotational velocity of about 100 km s^{-1} (Christopher et al. 2005). The observed CO and HCN (Güsten et al. 1987) emission indicates a total mass of $\sim 10^5$ M$_\odot$. However, HCN observations imply that there is high density material close to the inner edge (Christopher et al. 2005) suggesting that the mass may be closer to 10^6 M$_\odot$. The application of the formation scenario to the circumnuclear ring of gas argues that this disk was recently captured, is currently settling down and is on the verge of forming stars (Paper I, Paper III).

The extent of the ring suggests an initial migrating cloud speed towards the lower end of the 50–100 km s^{-1} range. The Hoyle-Lyttleton radius is about 12 pc which is similar to the

outer radius of the molecular ring. On this scale, one expects considerable asymmetry in the cloud material passing by Sgr A* during the capture event, with a corresponding reduction in the net cancellation of angular momentum during the capture process (cf. Bottema & Sanders 1986). At first sight our model suggests that the circumnuclear ring could become unstable to gravitational fragmentation (Paper I), but this assumes that it has kinematically relaxed. The velocity dispersion of the ring is $\sim$30 km s^{-1}, so that it is not unstable unless its mass is 10^6 M$_\odot$.

Methanol and water masers have recently been detected suggesting that star formation is taking place (Paper II). It appears that the circumnuclear ring is still in the process of settling down soon after formation. The ring's orbital time scale at 2 pc is $\sim 10^5$ yr, so this implies that the age of the ring is $\leq 10^6$ yr. If this is so, the remains of the original interloper cloud should lie within $\sim$ 100 pc of Sgr A*. One candidate is the +50 km s^{-1} molecular cloud which extends along the plane from the Galactic center to l$\approx 0.2^0$ and consists of a number of bound cloudlets with a total mass of $\sim 10^6$ M$_\odot$. This cloud is thought to lie about 30 pc behind Sgr A*, consistent with an interaction $\sim 3 \times 10^5$ years ago.

4. AGN Megamaser Disks

Recent VLBA observations have discovered several sub-parsec megamaser disks with high inclinations in the nuclei of Seyfert 2 galaxies (Herrnstein et al. 2008; Kuo et al. 2010). The inner and outer radii are determined by milli-arcsecond observations. The mass of the disks are measured accurately because these disks lie well within the sphere of influence of their host black holes and are not self-gravitating. Figure 2 shows an empirical linear correlation between the disk radius and the black hole mass. There is a well-defined upper envelope to the maser disk radii which scales linearly with black hole mass, given approximately by R$_{\rm max} \sim 0.3$ M$_7$ pc , where the central black hole mass is $M = M_7 \times 10^7$ M$_\odot$.

The remarkable similarity of size scale of the stellar disk surrounding Sgr A* and the megamaser disks suggest that they could be formed the same way. Paper III shows that for plausible estimates of the mass and angular momentum of the captured material, this process naturally reproduces the empirical linear relationship between maser disk size and black hole mass. The capture of clouds with column densities $\leq 10^{23.5}$ cm^{-2} results in a non-self-gravitating disks of the correct scale and sufficient column density to allow X-ray irradiation from the central source to reproduce thin megamaser disks. By contrast, the capture of a cloud with higher column density would instead create a self-gravitating disk giving rise to rapid star formation.

In the context of disk formation, the disk size scales with black hole mass. The reason for such a scaling is as follows. The mass of the disk depends on the Hoyle-Littelton capture radius and the column density of the initial cloud. The size of the disk depends on the capture radius which itself depends on the mass of the black hole and the angular momentum cancellation. Thus, the cloud capture model implies that the radius of the disk depends linearly on the mass of the black hole.

5. Cloud Migration

How do molecular clouds migrate toward Galactic nuclei? The inner 200 pc of the Galaxy is rich in dense molecular clouds, many of which are on eccentric orbits (Bally et al. 1988; Oka et al. 1998; Martin et al. 2004; Jones et al. 2011). In addition to the +50 km s^{-1} molecular cloud and other members of a disk population of molecular clouds distributed within the inner 30 pc of Galactic center. Their non-circular, elongated motion is thought to be induced by the Galaxy's barred potential (see Kim et al. 2011), with dynamical friction aiding migration to the central regions of the Galaxy. The bar potential of the Galaxy can apply a torque to the clouds, thus trigger infall toward the nucleus (see F. Combes in these proceedings). Recent simulations also suggest that gas supplied to galactic centers is controlled by angular momentum transfer from one massive gas clump to another during gravitational encounters (Namekata & Habe 2011).

In the context of a transition from X1 to X2 orbits, the gas clouds lose angular momentum spiraling in toward the central region of the Galaxy. In order to bring gaseous material close in to the inner few pc, the bar must be nested (Namekata et al. 2009).

Some of these inward-moving clouds may interact with their host supermassive black holes. In our own Galaxy, the circumnuclear molecular ring (e.g. Christopher et al. 2005) at a distance of 1.7 pc from Sgr A*, the 50 km s^{-1} molecular cloud, and the circumnuclear rings found on scales of several parsecs from the center of numerous Seyfert galaxies suggest an ample supply of material. The rate of migration of molecular material is estimated to be about $10^4 - 10^5$ $M_\odot$ per $10^6 - 10^7$ years. The age of the stellar disk (Paumard et al. 2006), and the relative youth of the circumnuclear ring (Paper II) is consistent with the age estimate implying that the rate of encounters of massive clouds with Sgr A* is $\sim 10^{-6}$ yr^{-1}. This may have been been ongoing for a significant fraction of the Galaxy's lifetime as the stellar population in the central parsec is consistent with roughly constant star formation over the past 12 Gyr (Maness et al. 2007).

6. Black Hole Recoil

The partial capture of a cloud with incident velocity $V_{initial}$ imparts momentum to the system of black hole with a mass M_{BH} and gaseous disk with a mass M_{Disk}, implying a kick velocity

$$V_{kick} = \frac{M_{Disk} \times V_{initial}}{M_{BH} + M_{Disk}} \tag{1}$$

to the black hole. Given that black holes like Sgr A* are embedded in their host nuclear cluster, the black hole is expected to move with respect to the center of the cluster and exchanges heat with the cluster due to dynamical friction. The recoil is of the order of few km s^{-1} and is likely to be damped via dynamical friction on the surrounding stars, on a timescale of the stellar crossing time across the sphere of influence, $\sim 10^3$ years. However, the parameter space for the significance of the recoil to the black hole in different nuclear cluster environment has not been explored.

7. Conclusions

In summary, we have investigated the capture of gas clouds by massive black holes via the Hoyle-Lyttleton process. We applied this mechanism to three different evolutionary phases of cloud capture scenario. One is a subset of AGN megamaser disks with high inclinations. There is no apparent star formation in these disks which lie within the sphere of influence of their host black holes. Second application of the cloud capture scenario is to the 2-parsec molecular disk orbiting Sgr A* where the gaseous disk is young. It has been argued that this system is showing early signatures of star formation. Lastly, sub-parsec stellar disk orbiting Sgr A* where massive star formation has already taken place a few million years ago.

The lack of star formation in megamaser disk systems could be due to strong magnetic fields acting against self-gravity of the disk (Johansen and Levin 2008; Gaburov, Johansen and Levin 2011). Alternatively, the low column density may be responsible. Assuming that the tidal shear by the black hole is accounted for, then the mass-to-flux ratio is an important parameter for the comparison of self-gravity and the magnetic field. Thus, the lack of star formation depends on the column density of incoming clouds and the magnetic field of the disks rotating around massive black holes. Future molecular line and magnetic field observations of thermal gas in these disks should be quite useful.

The physical relationship that threads through these different systems is the capture of a cloud by engulfing the massive black hole. This is an effective way to get rid of the angular momentum of the incoming molecular cloud. The engulfing scenario can also be applied when a star approaches the tidal disruption radius of a massive black hole. We speculate that these

processes could operate in galaxy mergers, dense stellar cusps around massive black holes, leading to starburst activity, black hole growth and powerful flaring activity in the vicinity of central massive black holes.

We found a scaling relation between the radius of the captured disk and the massive black hole which appears to be supported by the Hoyle-Lyttleton capture process. The outer radius of the captured cloud is understood in terms of a physical truncation of the disk because the scale determined kinematics of cloud capture depends linearly on the black hole mass. The apparent inner radius of the captured disk can be understood if the disk is warped in such a way that the inner disk does not get sufficient exposure to the central source of X-rays, to produce 22 GHz H_2O (Maloney et al. 2002). As for the disk of stars orbiting Sgr A*, the inner radius is 0.03pc. In this case, it is possible that the stars that are formed within the inner 0.03pc are influenced by dynamical processes. In fact, there is a cluster of B-type stars with eccentric orbits distributed isotropically within the inner radius but with a completely different distribution than that of the disk of stars. Alternatively, it is possible that the captured gas within the inner radius is dissipated to high temperature and does not have sufficient density to overcome the tidal stress. This idea could be relevant to the formation of the inner radius of the circumnuclear molecular ring where hot stars of the disk are thought to have ionized the inner 1.7pc of molecular gas and created a cavity of molecular gas in this region.

8. References

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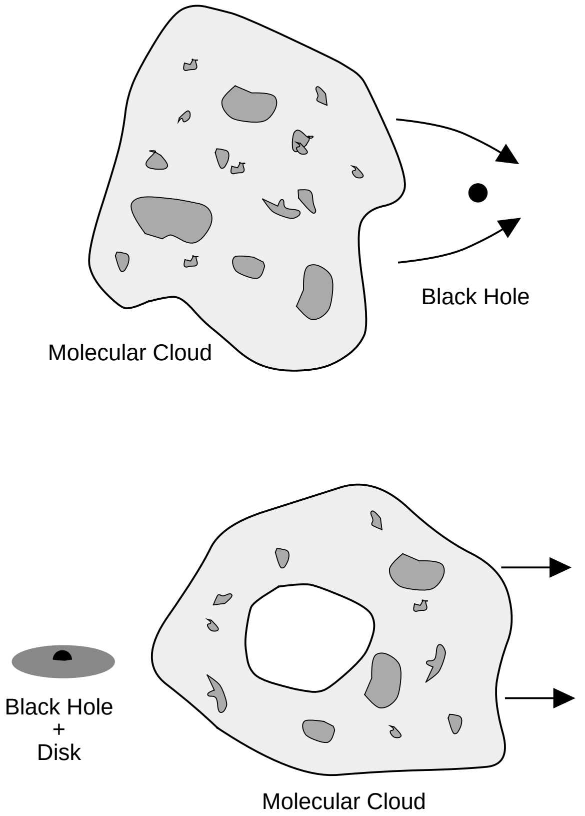

Figure 1. A schematic diagram of a cloud before and after impacting Sgr A*.

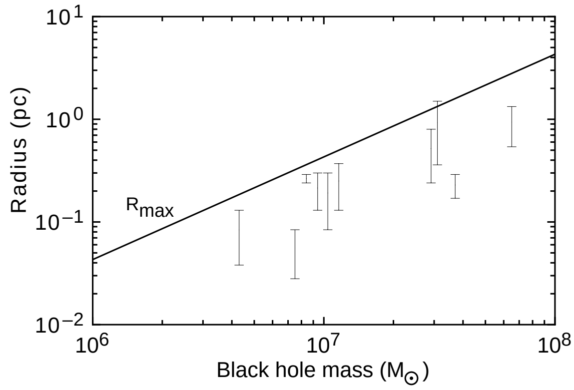

Figure 2. A plot of the black hole mass and the outer and inner radii of AGN mega-maser AGNs plus the Galactic center stellar disk. The upper envelope, labelled "$R_{\rm max}$", is given by $R_{\rm max} = 0.3(M/10^7 \mathrm{M}_\odot)$ pc.